Optimisation of CO_2 and Temperature in Terms of Crop Growth and Energy Use

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Abstract

In current greenhouse climate control, temperature set points follow a pre-set trajectory based on absolute or solar time parameters, adapted only to instantaneous and daily radiation. CO_2 is supplied during a well defined period of the day until a maximum concentration is reached. However, the rate of CO_2 supply is strongly limited by the heat demand, since flue gases are the most commonly used source of CO_2. Interactions between effects of light, temperature and CO_2 concentration on photosynthesis and crop growth are usually not taken into account. This study aims to make more efficient use of temperature and CO_2 by developing an optimised climate control system in which temperature and CO_2 are deployed such that energy use is minimised while maintaining crop production. Firstly, the diurnal temperature course resulting in a predefined daily mean value was optimised while minimising the heat demand. Most of the time, this resulted in higher day temperatures and lower night temperatures. Secondly, using the heat storage tank, the partitioning of the CO_2 associated with the daily heat demand was optimised, aimed at maximised photosynthesis. Simulation results showed that in the optimised climate control system 7% less energy was used and 2.5% more production was realised than in a standard climate. Testing the optimised climate control in a greenhouse experiment showed that in a sweet pepper crop 6% more energy could be conserved compared to that in the standard climate with similar production levels and fruit quality between the climate control treatments.

INTRODUCTION

In view of the Kyoto protocol (1997), Dutch horticulture and government have agreed to improve the energy efficiency by 65% in 2010 compared to 1980. Energy efficiency can either be enhanced through an increase in production or a reduction in absolute energy consumption. The latter implies that the availability of CO_2 from flue gases associated with the heating demand of greenhouses will be reduced. Hence, an efficient use of CO_2 is getting more important. At present, the greenhouse climate is commonly controlled by rather rigid set points for heating and ventilation. Climate control systems are set to limit temperature fluctuations, resulting in high ventilation rates when the sun is shining and in heating during the night. However, several studies have shown that most horticultural crops tolerate temporary deviations from the temperature set point, as long as the average temperature over 24 hours is kept constant (Bakker and Van Uffelen, 1988; Rijsdijk and Vogelezang, 2000). This so-called temperature integration allows heating to be shifted to times when the heat loss is low, thereby reducing the energy use (Körner and Challa, 2003a). Allowing the day time temperatures to increase, enables average 24 h temperature to be obtained at lower night temperatures. The decreased ventilation rates during the day result in higher CO_2 concentrations that can be realised with a certain rate of CO_2 supply, thereby increasing photosynthesis and crop production. On the contrary, the reduction in energy use will reduce the amount of fossil CO_2 for CO_2 supply. In the present study, a climate control system for optimal use of CO_2 and temperature was designed. This system was tested in a greenhouse experiment

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in which its effects on energy use and sweet pepper production were investigated.

MATERIALS AND METHODS

Simulation

An optimal climate control system was designed with KASPRO, a model describing the dynamics of the greenhouse climate, the heating system and the greenhouse climate controller (De Zwart, 1996). In this model, a module calculating the photosynthetic activity of the crop was implemented (Gijzen, 1994). Aim of the optimisation was to minimise energy use while maintaining crop production, for which photosynthesis was used as a measure. Performance of the optimised climate was compared to performance under settings used in commercial sweet pepper growing practice. Simulations were done for year-round grown sweet pepper crop (December – November). Given the outside climate (Breuer and Van de Braak, 1989), average 24 h temperatures and production (expressed as gross photosynthesis) under standard settings in the greenhouse were calculated. These were the basis for the optimisation of daily courses of temperature and CO_2 concentration. The first step was to optimise the daily course of temperature while yielding the same average 24 h temperature as the standard climate. In order to prevent deviations in growth and development, temperatures were not allowed to fluctuate beyond the range of 16 °C to 30 °C.

After optimising the course of temperature, resulting in a certain heat demand and, consequently, a certain amount of CO_2 present in the flue gases, the partitioning of that amount of CO_2 during the day was optimised. This optimisation procedure was based on an estimated efficiency of CO_2 supply on an hourly basis in terms of the relation between supply and effect on production. In this optimisation, the level of irradiance, temperature and CO_2 losses due to ventilation were taken into account. In general, effects of CO_2 on photosynthesis are higher at higher light intensities and higher temperatures (Gaastra, 1959). The optimisation made use of one day ahead weather forecasts, which were updated every 6 hours. Because of these frequent updates, the sometimes poor quality of the weather forecasts on longer term did not seriously affect the achievements of the optimisation procedure. The asynchrony between heat and CO_2 demand (heating is concentrated in night time whereas CO_2 is supplied during the day) was solved by means of a short term heat storage tank. Such devices, having a capacity of some 100 m^3 per hectare, are common practice in nowadays Dutch horticulture.

Experiment

Sweet pepper plants cv Solution were planted on rockwool slabs (Expert, Grodan) in week 7, 2003 in 2 greenhouse compartments of 180 m^2 each at a planting density of 3.4 plants m^{-2}. Plants were pruned back to two main branches per plant. The first 3 fruits were removed before fruit set. In the standard treatment, sweet pepper plants were grown with settings comparable to commercial practice. In the optimised climate, from week 14 onwards, temperature and CO_2 settings were calculated with the optimisation procedure as described in the previous paragraph. At 4-week intervals, 10 plants per compartment were harvested destructively. Plant length, leaf area and fresh and dry weights of stems, leaves and fruits were determined. From week 18 onwards, ripe fruits were harvested red. Number of fruits, fresh and dry weights and fruit quality were determined weekly. The experiment was ended in week 27. Since only one greenhouse compartment was used per treatment, statistical analysis of the data was not possible.

RESULTS

Simulation

The first step in optimising greenhouse climate was to optimise temperature such that with a minimal energy input, the average 24 h temperature of the reference climate could be realised. The optimisation procedure simply evaluated the effect of a large number of 24 hour temperature set point sequences with respect to heating demand in relation to the computed average 24 h temperature and selected the strategy that appeared to be the lowest energy demanding realisation of the required diurnal mean temperature. On sunny days this resulted in higher day temperatures in the optimised climate by using heat from the sun more than in the standard climate. Since we aimed at equal diurnal mean temperatures in both treatments, an increased day temperature required a lowered night temperature. Obviously, when temperatures were allowed to increase, ventilation during the day was reduced in the optimised climate (data not shown), which is favourable for the efficiency of the CO_2 supplied. The optimisation algorithm for CO_2 shifted the partitioning of the CO_2-dosing to the early hours of the day, leading to higher CO_2 levels during the morning compared to the standard climate (Fig. 1). Due to the increased utilisation of solar heat, the more efficient utilisation of CO_2 and the reduced ventilation, the simulation results of the optimised climate point to an annual reduction in energy consumption of 7% and a 2.5% increment of production (expressed as gross photosynthesis) compared to the results of the simulated standard climate.

Experiment

In the experiment, the average 24 h temperatures in both treatments (standard climate and optimized climate) were kept equal to prevent differences in plant development. The diurnal course of temperatures differed between the treatments (Fig. 2). During colder periods, daytime temperatures in the optimised climate were higher than in the standard climate, whereas night temperatures were lower (temperature integration).

During warm days, the optimisation algorithm was hardly able to influence the temperature course, since the maximum temperature was set at 30 °C. Daytime temperatures in the optimised climate were therefore limited, thereby consuming the space for lower night temperatures, since the average day temperatures between treatments had to be equal. This is reflected in the pattern of daily energy consumption in both compartments (Fig. 3).

In colder periods, the optimised climate used less energy than the standard climate did. If, however, the energy use was low (less than 0.07 m^3 gas [m^{-2} day^{-1}]), there is no difference in the energy consumption between the climates. This was due to the use of a minimum pipe temperature, which was equal in both compartments. During the experimental period (April – June 2003), the energy use in the optimised compartment was 7.5 m^3 gas m^{-2} and in the standard compartment 8.0 m^3 gas m^{-2}, an energy conservation of 6%, which was comparable to the energy saving percentage calculated in the simulation study.

Calculating the optimum diurnal course of temperatures yielded data on daytime ventilation losses of heat and CO_2. These data, combined with the diurnal course of irradiance and temperature were input for the photosynthesis module. The module calculated the effect of extra CO_2 on the photosynthesis for each moment of the day, thereby determining the CO_2 supply strategy. On warm days, this resulted in a shift of CO_2 supply from the afternoon to the morning in the optimised climate (Fig. 4). The optimisation of the CO_2 supply during the experiment resulted in a calculated increase in production (photosynthesis) of 2% for the optimised climate compared to the standard climate, which agrees well with the results of the simulation study.

Plant growth and development in terms of length, leaf area and fruit set were not affected by the climate treatments applied. Effects of the optimised climate and the standard climate on cumulative shoot and fruit dry weights could not be demonstrated (Fig. 5). The fraction of first class fruits in the optimised climate was slightly higher than in the standard climate (data not shown).

DISCUSSION

In recent years, several climate control strategies were developed aiming at optimising greenhouse climate and reduction of the use of energy. They were often based on the principle of temperature integration. Körner and Challa (2003a) developed a system with short-term and long-term temperature integration. The short-term integration (1 day) had a broad temperature range, whereas this was limited in the long-term integration (6 days). This modified temperature regime yielded 4.5 to 9% reduction in energy use compared to a regular temperature integration procedure (Körner and Challa, 2003a). This corresponds rather well with the 7% energy conservation resulting from our calculations. The reduction found by Körner and Challa (2003a) increased considerably when temperature control was combined with optimal humidity control in the greenhouse (Körner and Challa, 2003b). Rosenqvist and Aaslyng (2000) developed a dynamic greenhouse climate control system (IntelliGrow) based on the ability of the plant to adapt to changes in light, temperature and CO_2 concentration. Temperature and CO_2 concentrations are adjusted to the prevailing light conditions based on the interactions between light, temperature and CO_2 concentrations on photosynthesis (Ottosen et al., 2003). In general, the IntelliGrow strategy can be summarised as optimal use of CO_2 under high light conditions for optimal production and low temperatures under low light conditions to conserve energy (Rosenqvist & Aaslyng, 2000). Testing the strategy in a sweet pepper experiment showed that up to 20% energy conservation was possible, but fruit quality was reduced, probably due to the high daytime temperatures (Ottosen et al., 2003). In our study, we found no negative effects on fruit production or quality. In the optimisation procedure we used, energy conservation was limited by the upper temperature limit, which was set at 30 °C. This limited the possibilities for temperature reduction at night, which partly might have caused the differences in energy saving percentages between our study and the IntelliGrow approach. However, commercial growers are not likely to accept losses in fruit production or quality. Therefore, temperature limits in application of temperature integration have to be chosen carefully to make grower adopt this strategy. Only then can a reduction in energy use by means of optimal greenhouse climate control strategies be realised.

ACKNOWLEDGEMENTS

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Figures

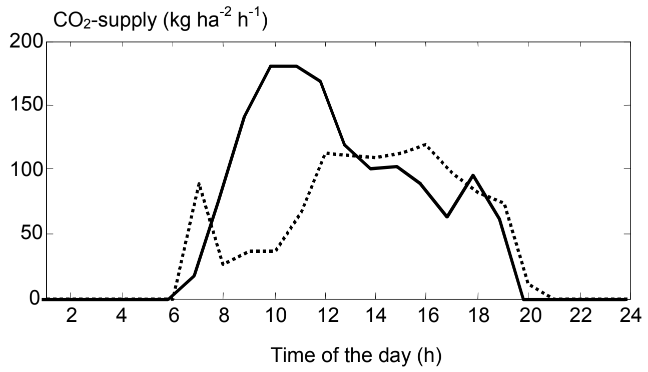

Fig. 1. Course of CO_2 supply in the standard climate (- -) and the optimised climate (—).

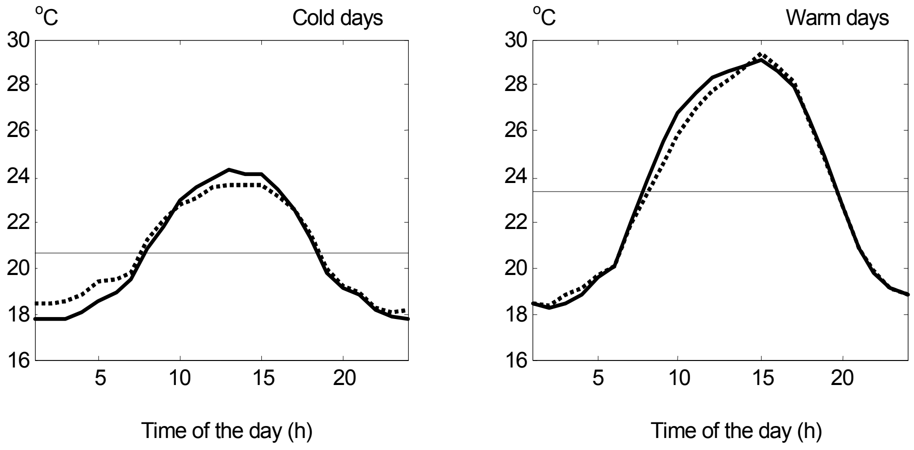

Fig. 2. Average course of air temperatures on 48 relatively cold days (left) and 32 relatively warm days (right) in the standard climate (- -) and in the optimised climate (—). The horizontal line marks the average 24 h temperature.

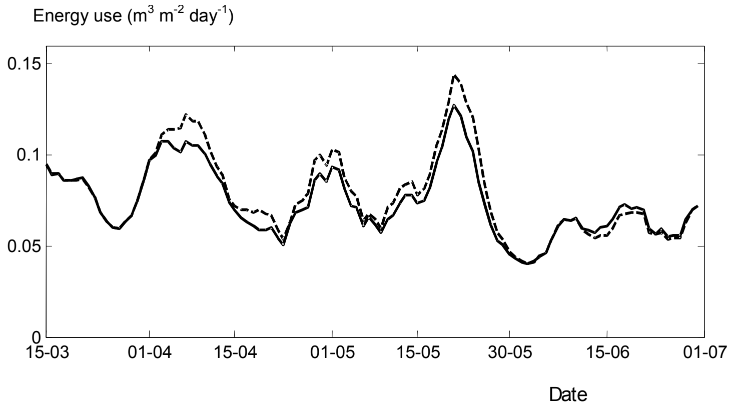

Fig. 3. Daily energy use in the standard climate (- -) and in the optimised climate (—).

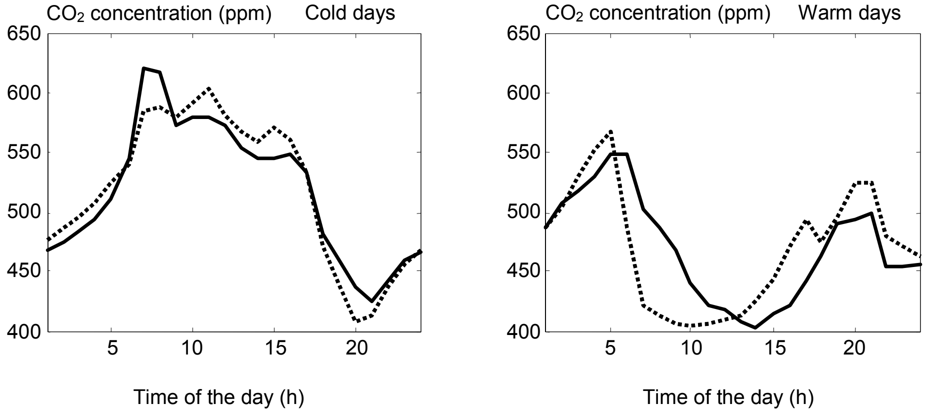

Fig. 4. Daily course of CO_2 concentration in the greenhouse on 48 relatively cold days (left) and 32 relatively warm days (right) in the standard climate (- -) and in the optimised climate (—).

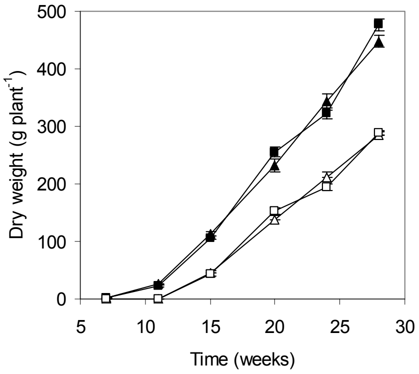

Fig. 5. Course of cumulative total plant dry weights (■▲) and cumulative fruit dry weights (□Δ) of sweet pepper plants grown in the standard climate (■□) and in the optimised climate (▲Δ). Vertical bars indicate standard errors of means.